Ambient Vibration Measurements for Estimation of Site Fundamental Periods – Case History of the City of Mayagüez, Puerto Rico

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SUMMARY:
This paper presents the result of an experimental program based on the determination of the fundamental soil vibration period from ambient vibration measurements at close to 150 selected sites within the City of Mayagüez, Puerto Rico. The work is an extension of a pilot study presented at the 14th WCEE in Beijing, China where initially predominant vibration periods were estimated for six strong motion seismic stations located in the same city. However to allow for the development of an isoperiod map for this city a denser grid of data points was required. This was accomplished by means of ambient vibration measurements using portable triaxial accelerometers and the application of the H/V spectral ratio technique to determine the predominant vibration period at over 150 sites within Mayagüez. The final outcome of the experimental program was a detailed soil isoperiod of vibration map for Mayagüez which can be used for seismic risk assessments and microzonation studies. This case study is considered useful due to its cost effectiveness and relevance for a Caribbean city located in a zone of high seismicity.

Keywords: Ambient vibrations, microzonation, isoperiod maps, Caribbean seismicity.

1. INTRODUCTION

The intensity of ground motion is a function of parameters such as the magnitude of earthquake, the epicentral distance, the characteristics of the seismic source, and local site effects. It is well documented that local site effects are a key consideration to carry out reliable seismic hazard analyses (SHA). However, in practice SHA often only have availability to limited data for a given site. In recent years a popular approach to assess local site effects has been to use seismic instrumentation (geophones, seismographs or accelerographs) to monitor either microtremors (a term used herein as equivalent to ambient seismic noise or low amplitude vibrations) or weak-motion earthquakes at the site of interest (e.g., SESAME, 2004). This approach has been particularly useful for areas with low seismic recurrence where data of strong motion earthquakes is limited or not available. Such is the case for Puerto Rico, a Caribbean island that is considered to have high seismic potential but with no strong motion data available. This paper presents a case history which is an extension of a pilot study presented at the 14th WCEE by Pando et al. (2008). Specifically, this paper presents the results of close to 150 sites where ambient vibration (AV) measurements were recorded, analyzed, and processed using the H/V spectral ratio technique described in Pando et al. (2008). The main deliverable from this relatively low cost effort was a map of soil predominant period of vibration, referred herein as isoperiod map, for the city of Mayagüez. The study outcome provides a valuable tool for quantification of site effects on seismic hazard that can be used by the local engineering design community and policy makers to prepare for future seismic events in the densely populated city of Mayaguez, Puerto Rico.

2. OVERVIEW OF THE HORIZONTAL/VERTICAL SPECTRAL RATIO (HVSR) METHODOLOGY USED FOR ESTIMATING THE SITE PREDOMINANT PERIODS

This popular method is commonly referred to as the “Nakamura technique”, as it is commonly attributed to Nakamura (1989). The method in essence involves computing the spectral ratio between the horizontal and vertical components of the recordings at the site of interest. No bedrock site of reference is required for application of this technique (a detailed description was provided by Nakamura 2000 and 2008). The literature shows that the technique has been used primarily with microtremors recordings but it has also been applied to earthquake records. Nogoshi and Igarashi (1971) for example compared the peaks of H/V spectral ratios obtained from surface wave recordings with microtremors. The authors reported good correlations were obtained between H/V spectral ratios from the fundamental mode of the Rayleigh waves and the ones obtained from microtremors at sites with a high impedence contrast. The methodology applied to microtremors was studied in considerable detail in the European research project SESAME (SESAME, 2004).

Nakamura (1989, 2000) proposed the HVSR from Equation 2.4 as a reasonable estimate of the predominant period of a site based on a series of assumptions. Figure 2.1 shows the geometry of the problem, and the site where the predominant period is desired.

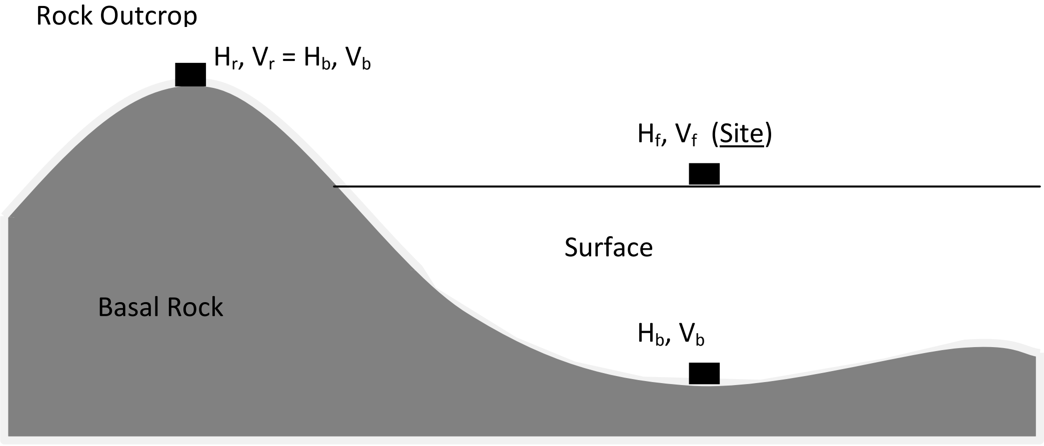


Figure 2.1. Sketch showing sedimentary basin geology considered by Nakamura (2000)

Nakamura postulates that waves that produce the ambient vibrations recorded at a soil site are primarily of two types: i) surface waves (specifically Rayleigh waves); and ii) body waves (P and S waves). In other words, Nakamura (2000) expressed the horizontal movement (H_f) and vertical (V_f) at the free surface of the soil site shown in Figure 1, as the sum of the movement from the body waves that travel from the basal rock plus the movement from the surface waves. This superposition is convenient to do it in the frequency domain. Thus, $H_f(\omega)$ and $V_f(\omega)$ are respectively the Fourier Transforms of the horizontal and vertical components of the movements recorded at the ground surface of the site. And as mentioned before they include the contributions from both body and surface waves. The spectra of $H_f(\omega)$ and $V_f(\omega)$ are not useful for identifying the natural frequencies of the soil deposit as they also contain the dominant frequencies of the sources that generated the waves.

If ground motion recordings from the basal rock shown in Figure 2.1 were available, with the corresponding Fourier spectrum, i.e., $H_b(\omega)$ and $V_b(\omega)$ one could obtain the following spectral ratios:

$$T_h(\omega) = \frac{H_f(\omega)}{H_b(\omega)} \quad ; \quad T_v(\omega) = \frac{V_f(\omega)}{V_b(\omega)} \tag{2.1}$$

Which represent the transfer functions between the motions at the surface and the basal rock, for both the horizontal component ($T_h(\omega)$) and the vertical component ($T_v(\omega)$), which eliminate the so called source effects, thus allowing determination of the natural frequencies of the deposit. However, basal rock movements are commonly not available. Nakamura (2000) considers that $H_b(\omega)$ and $V_b(\omega)$ are equal to the spectrum obtained at a rock outcrop (See Figure 2.1), and he refers to these as $H_r(\omega)$ and $V_r(\omega)$. This may be considered a reasonable approximation, but rigorously speaking this assumption is not correct. The frequencies of the peaks do coincide, but the magnitudes of the peaks of $H_r(\omega)$ and $V_r(\omega)$ are smaller than those from $H_b(\omega)$ and $V_b(\omega)$.

Due to the difficulties of obtaining Fourier spectrum from the basal rock, Nakamura (2000) proposes the use of a frequency function defined as the ratio between the transfer functions $T_h(\omega)$ and $T_v(\omega)$ (defined in Eq. 2.1):

$$T_h^*(\omega) = \frac{T_h(\omega)}{T_v(\omega)} \tag{2.2}$$

Replacing the expressions from Eq. (2.1) into Eq. (2.2) we obtain:

$$T_h^*(\omega) = \frac{T_h(\omega)}{T_v(\omega)} = \frac{H_f(\omega)\big/H_b(\omega)}{V_f(\omega)\big/V_b(\omega)} = \frac{H_f(\omega)}{V_f(\omega)}\frac{1}{H_b(\omega)\big/V_b(\omega)} \tag{2.3}$$

Using results form his own experimental field measurements Nakamura (2000) suggested that the spectral ratio between horizontal ($H_b(\omega)$) and vertical ($V_b(\omega)$) basal rock motions is approximately equal to unity, or at least Nakamura considered this assumption as reasonable for the range of frequencies near the predominant frequency of the site (ω_o). This assumption was later confirmed by Lermo and Chávez-García (1994) and by Huang and Teng (1999).

Therefore, considering a basal rock H/V spectral ratio of unity, the ratio $T_h(\omega)/T_v(\omega)$ becomes:

$$T_h^*(\omega) = \frac{T_h(\omega)}{T_v(\omega)} = \frac{H_f(\omega)}{V_f(\omega)} \tag{2.4}$$

Nakamura (2000) referred to the $H_f(\omega)/V_f(\omega)$ ratio as “Quasi Transfer Spectrum” or QTS. However, the engineering community usually refers to this spectral ratio simply as H/V.

It can be proven empirically or theoretically, that independently of the type of waves involved, or their relative importance in the ground surface motions recordings $H_f(\omega)$ and $V_f(\omega)$, that the quasi transfer spectrum or H/V ratio will present a peak at the predominant frequency of the soil deposit (ω_o).

3. DESCRIPTION OF THE STUDY AREA (CITY OF MAYAGÜEZ)

3.1. Motivation for the study

The city of Mayaguez is considered to be at a significant seismic risk due to several factors such as: i) a long history of large, damaging earthquakes and continuing seismicity, as well as pre-historic evidence of strong ground shaking; ii) several sources of earthquake shaking in the vicinity of the city of Mayagüez, each capable of producing very strong ground motions; iii) time elapsed since the last major destructive earthquake (1918) exceeds the recurrence period estimated on the basis of historical seismicity; iv) several areas of the Mayagüez region contain thick, soft alluvial sediments (Pando et al. 2006), which could greatly amplify earthquake ground motions and increase damage potential; and v) the large population (absolute and terms of density) of the largest city in Western Puerto Rico.

Key elements associated with the seismic hazard assessment for the Mayagüez region are the estimation of the expected levels of ground motions including local site effects and the determination of associated potential damage due to amplifications and/or liquefaction. Thus the importance to better quantify local site effects through microzonations in terms of predominant site periods.

3.2. General description of the study area

Mayagüez is located on one of the coastal valleys of the west side of the Island of Puerto Rico. The city limits extend about 14 km from east to west and 13 km from north to south. The population is about 100,000 inhabitants of which about 33 percent lives in the downtown area (Census 2000). The topography of the Mayagüez area can be described as mild to flat sloped terrain in its coastal region and along the alluvial valleys. However mountainous terrain exists in the east and northeast parts of the city, with numerous dwellings located in these areas.

The coastal deposits are found along the coast of the Mayagüez Bay. The other low lying areas of the region, which are the alluvial valleys, are found on the lands surrounding the principal rivers of the area, called Yagüez and Guanajibo Rivers, as they were formed by the deposition of alluvial deposits from these rivers. The widest portion of the coastal plain or flatland is at the mouth of the Guanajibo River, which is located at the south part of the Mayagüez city. On the other hand, the central range of mountains is located on the east part of the city starting near the coastal area and rapidly rising to 350 meters above mean sea level. Detailed information of the geology and geotechnical conditions of Mayagüez is provided in the ArcView geotechnical database of the city by Pando et al. (2006).

3.3. Seismicity of the study area

The island of Puerto Rico (PR) is located in a very active and complex tectonic region in the northeastern Caribbean Sea. Most of the seismic activity of the area is produced by the convergence and lateral translation of the North American and Caribbean Plates beneath the Puerto Rico Platelet (Tuttle et al., 2003). Figure 3.1 shows how PR is surrounded by several offshore active faults which are considered the major sources of seismic activity on the island. For example, the Mona Canyon and the Anegada Passage are extension zones located to the west and east side of the island, respectively. Also surrounding the island are two subduction zones to the north and south side of PR called the Puerto Rico Trench and Muertos Trough, respectively. Inland seismic sources include segments of the Great Southern Puerto Rico Fault Zone (GSPRFZ) and Great Northern Puerto Rico Fault Zone (GNPRFZ) that cross the island from northwest to southeast. Additional to the seismic sources mentioned above, an inland source has recently been identified as capable of generating M 7.0 events (Prentice and Mann, 2005). This inland fault is identified in Figure 3.1 as SLF for the abbreviation of South Lajas Fault which is located in the southwest corner of PR.

Based on the above seismic setting, PR is recognized as having a significant seismic hazard, as evidenced by the hundreds of moderate (M 4 to 5) events recorded in the last 30 years (PRSN 2012). Since the early Spanish settlements in the 16th century, at least five strong earthquakes have struck PR – 1670, 1787, 1867 ($M_w \sim 7.3$), 1918 ($M_w = 7.3$), and 1943 ($M_w = 7.5$) - causing loss of life and significant property damage (Asencio 1980, McCann 1987). Recent discoveries of what are believed to be evidence of ancient liquefaction features in western PR near the city of Mayagüez suggest that additional prehistoric earthquakes may have also occurred (Tuttle et al. 2003). The most damaging earthquake affecting Puerto Rico was the Aguadilla-Mayagüez Region earthquake of October 11, 1918. This earthquake killed 116 people, and caused an estimated $4 million (1918 dollars) in property damage (Reid and Taber 1919).

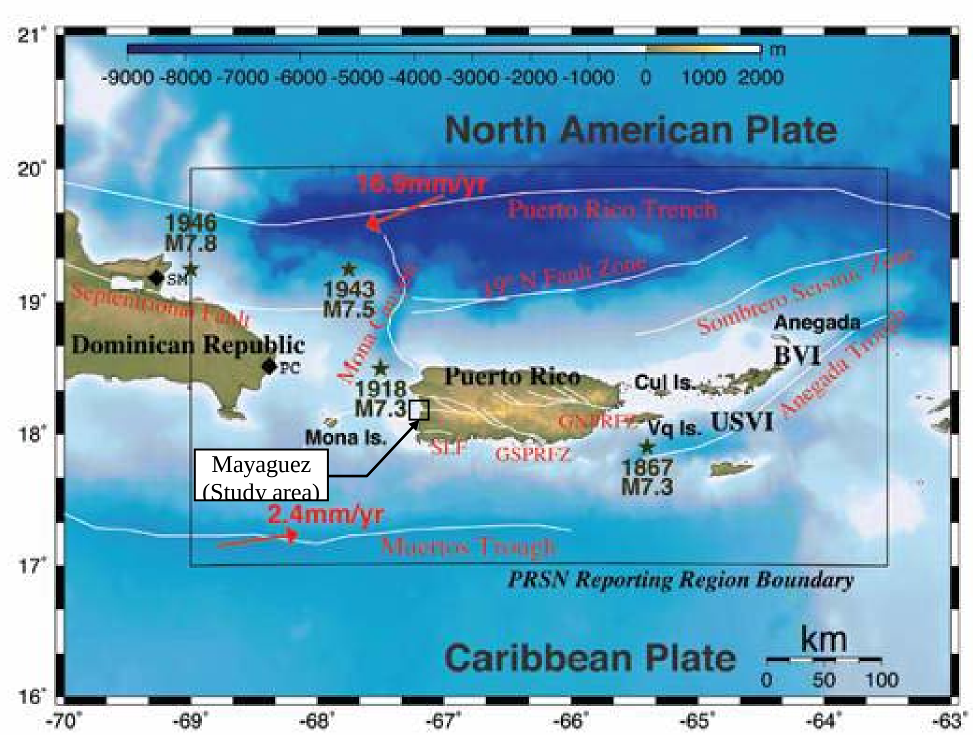


Figure 3.1. Seismic Settings and Major Faults (From Clinton et. al., 2007)

The consequences of a future large magnitude earthquake are considered more severe than the 1918 earthquake. Since 1918 the population of Mayagüez has increased six fold to over 100,000. Furthermore the vast majority of the buildings in the Mayagüez metropolitan area are located in the coastal plain area where potentially liquefiable deposits of very loose, saturated sands have been identified as well as thick, alluvial deposits that could amplify earthquake ground motions. Despite its high seismic risk, research to adequately assess and mitigate earthquake hazard in Western Puerto Rico lags behind other seismically-active regions of the US, particularly quantification of expected ground motions and liquefaction susceptibility. The efforts presented in this paper hope to contribute towards help filling this important gap.

3.4. Pilot study

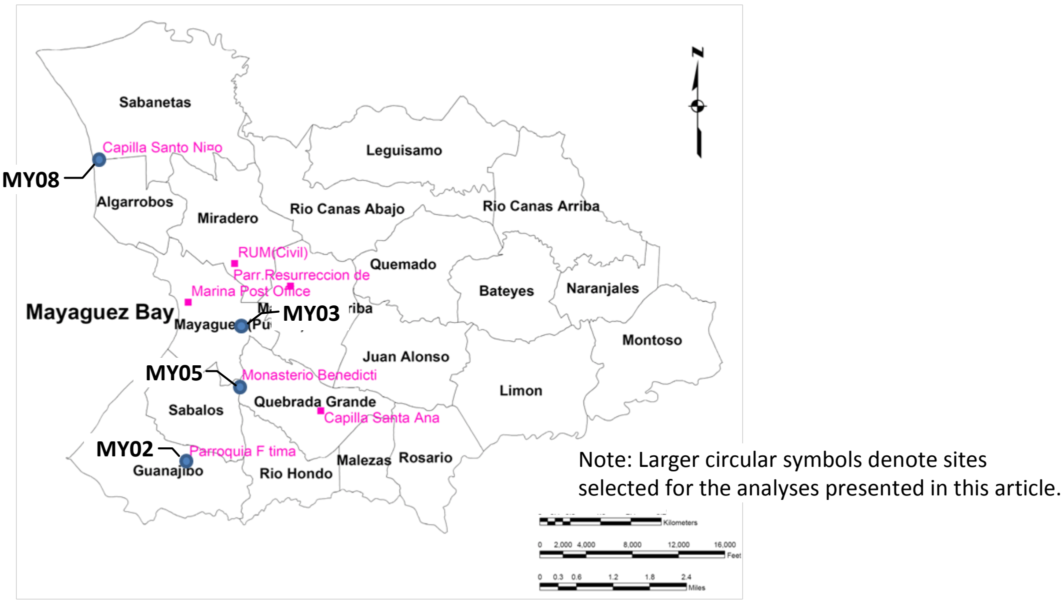
Prior to the implementation of the full scale ambient vibration study, a small pilot study involving ambient vibration measurements was carried out using recordings from four strong motion seismic stations in Mayagüez. Specifically the pilot project compared estimates of predominant site periods using different techniques using ambient vibration and also weak motion measurements recorded at some of the seismic stations. Specifically this study, presented at the 14WCEE by Pando et al. (2008), involved comparison of predominant site periods using the Fourier amplitude spectra, the Fourier spectral ratios between the spectra at the site and at a reference station, and the spectral ratios between the horizontal and the vertical components of ambient vibrations, i.e., the Nakamura's technique. The four strong motion sites analyzed are listed in Table 3.1 and locations shown in Figure 3.2. The estimated predominant site periods, computed using the methodology described in Section 2, for the four recording sites are summarized in Table 3.2. The table presents results in two groups: estimates based on weak motion earthquake recordings and estimates using ambient vibrations (micro-tremors).

In general all methods considered in the pilot study provided reasonably comparable estimates of the predominant site period or frequency. Some methods had better resolution than others facilitating the selection of the predominant period or frequency. Being able to reliably predict predominant site periods from microtremors is an advantage for seismic regions like PR where there is a low recurrence rate and there is no strong motion data. More details on the pilot study can be found in Pando et al. (2008).

Table 3.1. Strong motion sites analyzed in Mayagüez Pilot Study (from Pando et al. 2008)

Station Name	Abbrev.	Geographic Coordinates	Sensor Type	Trigger[1] Level (%g)	Ground conditions[2]
Fatima Parish	MY02	N 18.167150 W 67.151370	Triaxial EpiSensor	H = 1.0 V = 0.2	NEHRP soil class: D Topography: Leveled
Santo Niño de Praga Chapel	MY03	N 18.240750 W 67.172200	Triaxial EpiSensor	H = 1.0 V = 0.2	NEHRP soil class: F Topography: Leveled
Benedictine Monastery	MY05	N 18.185450 W 67.138030	Triaxial EpiSensor	H = 1.0 V = 0.2	NEHRP soil class: B/C Topography: Top of hill
Cathedral Parish House	MY08	N 18.200178 W 67.137512	Triaxial EpiSensor	H = 1.0 V = 0.2	NEHRP soil class: E Topography: Leveled

Notes: (1): Trigger levels reported are the operational values used by the PRSMP. For ambient vibrations the trigger levels were removed to ensure continuous recording. H = horizontal component, V = vertical component. (2): NEHRP soil classification as per BSSC (2001). NEHRP site classes for the sites are based on Pando et al. (2006).



Note: Larger circular symbols denote sites selected for the analyses presented in this article.

Figure 3.3. Location of 4 strong motion stations analyzed in Mayagüez pilot study (Pando et al. 2008).

Table 3.2. Summary of Pilot Study Predominant Site Periods and Frequencies (from Pando et al. 2008)

Station	NEHRP Class	Estimates based on weak earthquakes			Estimates based on microtremors		
		SRRS	HVSR-WM	WAVELET	FTS-AV	HVSR-AV	MTFR-RID
MY02	D	0.21 s (4.78 Hz)	0.31 s (3.21 Hz)	0.21 s (4.75 Hz)	0.21 s (4.87 Hz)	0.18 s (5.57 Hz)	0.20 s (5.03 Hz)
MY03	F (E)	0.56 s (1.77 Hz)	0.52 s (1.94 Hz)	0.63 s (1.60 Hz)	0.37 s (2.70 Hz)	0.39 s (2.55 Hz)	0.45 s (2.2 Hz)
MY05	B/C	Ref.	0.19 s (5.32 Hz)	0.13 s (8 Hz)	0.10 s (10.0 Hz)	0.10 s (9.7 Hz)	0.19 s (5.4 Hz)
MY08	E	0.28 s (3.60 Hz)	0.27 s (3.74 Hz)	0.27 s (3.75 Hz)	0.27 s (3.73 Hz)	0.27 s (3.70 Hz)	0.28 s (3.61 Hz)

Notes: FTS = Direct interpretation of Fourier spectrum; SRRS = Spectral ratios with respect to a rock reference site (Kagami); HVSR = Horizontal-to-Vertical spectral ratios at a given site (Nakamura); WM = weak motions; AV = Ambient Vibration; WAVELET = wavelet-based method of Montejo and Suarez (2006); MTFR-RID = Method by Cano (2008); Ref.= reference site.

Based on the good results from the pilot study a full scale study based on ambient vibration monitoring was carried out for the whole city of Mayaguez. The following section presents a summary of the results of the detailed study which is the main focus of this paper.

4. RESULTS

4.1. Measurement procedure and data processing

All ambient vibration measurements were made using triaxial ETNA accelerographs manufactured by Kinemetrics Company. These instruments have an internal GPS which was used to register the location of each measurement. At each test location ambient vibrations were registered for a period of 60 minutes at a data sampling rate of 100 samples per second which corresponds to a Nyquist frequency of 50 Hz. The accelerograph was always either placed directly on top of soil or grass or a steel plate at sites with pavements as per recommendations by Chatelain et al. (2008).

The procedure for processing the ambient vibration recordings requires several steps, such as: signal corrections, sampling window selections, signal filtering (e.g., Hanning window), computation of Fourier spectra of the three components, smoothing, computation of H/V ratios (see Eqn. 4.1 below), and calculation of mean and standard deviation of the H/V spectral ratios. This process has been automated in an in-house program written in Matlab. The H/V ratio is usually defined as:

$$\frac{H}{V} = \sqrt{\frac{H_{E-W}^2 + H_{N-S}^2}{2 \cdot V^2}} \tag{4.1}$$

where $H_{E\text{-}W}$ and $H_{N\text{-}S}$ are, respectively, the horizontal spectral values in the E-W and N-S directions and V is the spectral value in the vertical direction.

To avoid interference from point sources such as pedestrians, nearby traffic or machinery, amongst others, the Matlab program incorporated an automatic algorithm for selection of sampling windows (commonly known as “antitrigger” algorithm). This algorithm detects transitory point sources and eliminates them form the signal based on a comparison of amplitude averages. One average is based on an average over a short time period (STA, or short term average), and an average over a long time period (LTA, or long term average). When the ratio of the two averages, i.e., the ratio STA/LTA exceeds a previously established threshold, a point source event is considered to be detected. This criterion for selecting sampling windows is also used in the software JSesame, developed by the previously mentioned European project SESAME. For this module, the user must enter a series of parameters listed in Table 4.1. The values used for this project are also listed in this table.

Table 4.1. Parameters used for the processing of the ambient vibration records.

Window Length (sec.)	20
Overlap Window (% Window Length)	10
Window Length for the short term average (sec.)	1
Window Length for the long term average (sec.)	25
Minimum level for STA/LTA threshold	0.5
Maximum level for STA/LTA threshold	2

To check the influence of the results based on ambient vibrations measurements taken at different times of the day one of the stations was monitored for 24 hours and the data processed considering different 1 hour windows of data. The results of this stability analysis are shown in Figure 4.1. This figure shows the results after processing twelve 1-hour windows. The results show that H/V ratio provides the same predominant frequency, independent of the time of the day when the 1 hour window of ambient vibrations was recorded. However, the amplitude of the H/V peak does vary with the time of the day of the window of data considered. This finding is similar to reports by Kanai and Tanaka (1961), and Nakamura (1989).

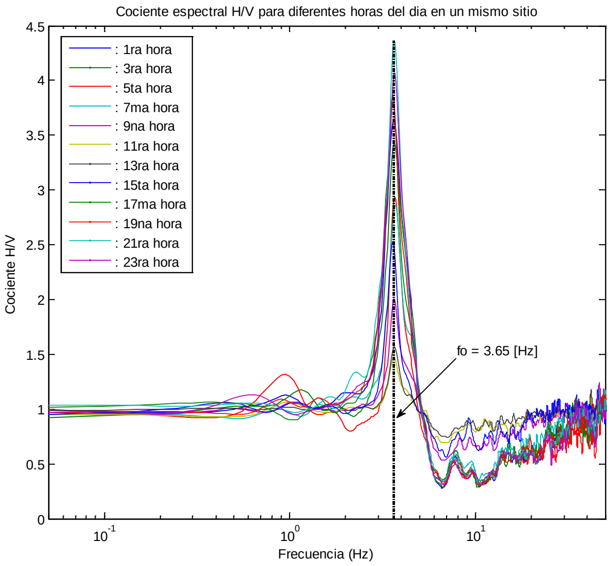


Figura 4.1. H/V Spectral Ratios for different times of the day at the Mayagüez Cathedral seismic station.

4.2. Test sites

The locations of the sites where ambient vibrations were recorded are shown in Figure 4.2. The area of the map with a denser arrangement of points corresponds to the areas with higher population density and the downtown area of the city.

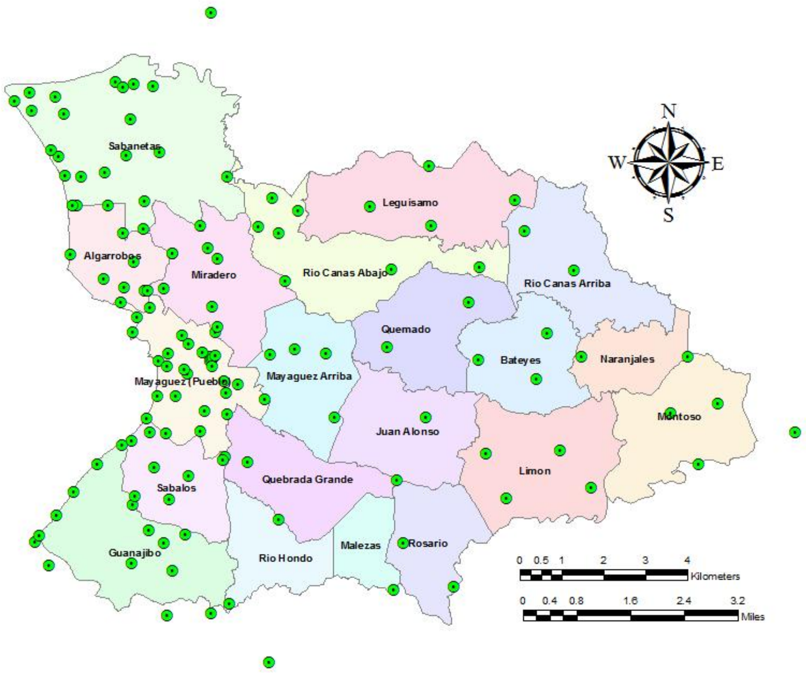


Figure 4.2. Site map showing location of ambient vibration measuring stations.

4.3. Isoperiod maps for the city of Mayaguez

A map showing graphically the predominant site period as a solid black circle with its diameter proportional to the period value is shown in Figure 4.3. As expected, this figure shows the longer site periods are located in the coastal regions where deep, soft, alluvial deposits or thick beach sand deposits are present. The smaller site periods are located to the east where the terrain is mountainous and the site conditions typically consist of residual soils underlain by shallow bedrock (Pando et al. 2006).

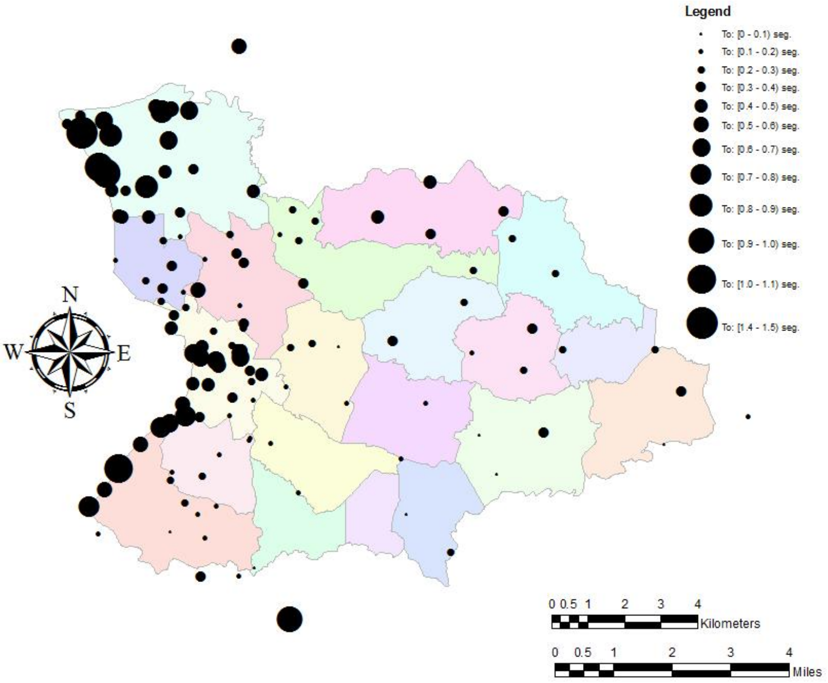


Figure 4.3. Map of predominant periods for the city of Mayaguez.

A map showing iso-period contours, i.e., contours of equal predominant site period, was also developed as part of this study. This map is shown in Figure 4.4. It can be seen that the results in Figures 4.2 and 4.3 are in good agreement.

However, for both maps, the user needs to exercise caution when using data based on interpolation between measuring stations. This is particularly important in the mountainous areas of the city where topography and geology can vary very quickly in short lateral distances. Thus the results presented in these maps are intended for preliminary estimates, and should not substitute site specific measurements and site investigations.

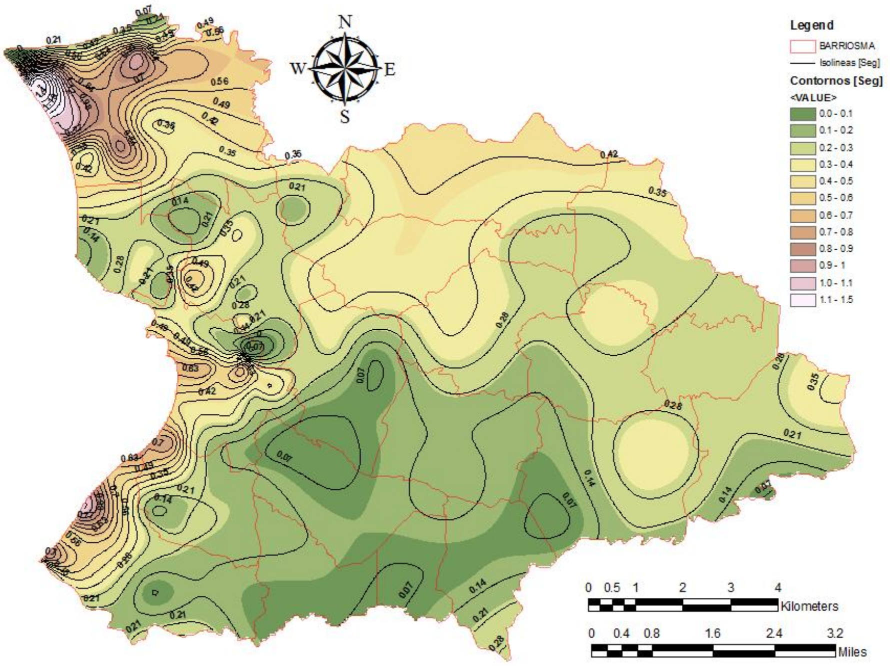


Figure 4.4. Map of Fundamental Iso-periods for the City of Mayagüez.

5. SUMMARY AND CONCLUSIONS

The papers presents a case history involving the use of a relatively inexpensive technique based on ambient vibrations measurements to develop maps of predominant site periods. The results were compared with geology and geotechnical data and also with other available techniques during a preliminary pilot study. The maps developed as part of this study will become a key tool for the seismic hazard assessment studies in the Mayagüez region including the estimation of the expected levels of ground motions due to local site effects which can be estimated on a preliminary basis from the predominant site periods provided by the maps.

ACKNOWLEDGEMENTS

The field work carried out for this study was funded by NEHRP USGS research grant 10HQPAQ0001 and from student funding and equipment access from the Puerto Rico Strong Motion Program. The authors gratefully acknowledge this support.

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